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TESTS WITH AN EXPERIMENTAL WHEEL ON CLAY

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TESTS WITH AN EXPERIMENTAL WHEEL ON CLAY

by

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ARMY-MRC VICKSBURG, MISS.

Foreword

The study reported herein was funded by Department of the Army Project 4A013001A91D, "In-House Laboratory Independent Research (ILIR) Program," Item T, sponsored by the Assistant Secretary of the Army (R&D). The study was conducted during 1969 and 1970 and is a continuation of the research reported in U. S. Army Engineer Waterways Experiment Station (WES) Technical Report M-69-2, "Improved Wheel Performance on Sand by Controlled Circumferential Rigidity," dated May 1969.

The test program was carried out by personnel of the Mobility Research Branch (MRB), Mobility and Environmental (M&E) Division, WES, under the general supervision of Messrs. W. G. Shockley and S. J. Knight, Chief and Assistant Chief, respectively, M&E Division; and under the direct supervision of Dr. D. R. Freitag, former Chief, MRB, and now Chief, Office of Technical Programs and Plans, WES, and Dr. K. W. Wiendieck, MRB. Dr. Wiendieck prepared this report.

COL Levi A. Brown, CE, and COL Ernest D. Peixotto, CE, were Directors of WES during this study and preparation of this report. Mr. F. R. Brown was Technical Director.

Contents

Conversion Factors, Metric to British and British to Metric Units of Measurement

Metric units of measurement used in this report can be converted to British units as follows:

Multiply	By	To Obtain
centimeters	0.3937	inches
meters	3.2808	feet
newtons	0.225	pounds
meter-newtons	0.7376	foot-pounds
kilonewtons per square meter	1.4503	pounds per square inch

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
inches	2.54	centimeters
pounds	4.448	newtons
pounds per square inch	6.895	kilonewtons per square meter

Summary

An extension of a previous study on sand, this report summarizes the test results obtained on clay with an experimental wheel with controlled circumferential rigidity. The test program was carried out for the sake of completeness despite the fact that the underlying principle of the experimental wheel was based upon sand properties and, therefore, similar wheel performance variations as a function of tire rigidity distribution were not to be expected on clay. In addition, insufficient torque capacity of the wheel-drive system prevented the performance criteria used in the sand study from being applied in this study on clay.

The relation of pull/load to efficiency was the only feasible relation that could be used in this investigation. As expected, no noticeable change in tire behavior could be observed for rigidity pattern variations. Control of tire rigidity distribution at the interface is not effective in clay. Although this conclusion is negative, it confirms the earlier findings on the improvement of performance of the wheel with controlled circumferential rigidity in sand.

TESTS WITH AN EXPERIMENTAL WHEEL ON CLAY

Background

1. Stress distribution patterns over the contact area of pneumatic tires on sand have been observed to vary in a characteristic manner with tire inflation pressure. Generally, at high inflation pressures the distribution of the normal stresses exhibits a maximum near the center of the contact area, and the reverse situation (high pressure ridges along the periphery, minimum pressure near the center of the contact area) occurs beneath low-inflated tires in otherwise identical conditions (fig. 1).

2. A detailed analysis of this phenomenon in tests on sand* led to the conclusion that the tire rigidity distribution pattern (which varies with inflation pressure) is partially responsible for the stress distribution. In fact, the observation was that the normal stresses tend to concentrate in areas of higher-than-average local tire rigidity, resulting sometimes in an almost perfect qualitative correspondence between rigidity and stress patterns for tires on sand.

3. To take advantage of this observed phenomenon, an experimental wheel was developed at the U. S. Army Engineer Waterways Experiment Station (WES) that allowed control of rigidity distribution patterns at the tire-soil interface within certain limits. Six nonrotating hydraulic jacks arranged in a roughly radial manner inside the tire acted against the inner side of the rolling belt (fig. 2) to influence the stresses by controlling the local tire rigidity within the contact area. This experimental wheel and its performance in terms of maximum pull/load (P/W) ratio and efficiency (E)** are fully described in Technical Report M-69-2.*

4. In accordance with theoretical considerations also presented in Technical Report M-69-2,* a tire rigidity pattern exhibiting a steady increase from the leading to the trailing edge of the contact area (favorable rigidity distribution) generates up to 25% higher performance than the

* K. W. Wiendieck, "Improved Wheel Performance on Sand by Controlled Circumferential Rigidity," Technical Report M-69-2, May 1969, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

** Efficiency is defined in paragraph 20.

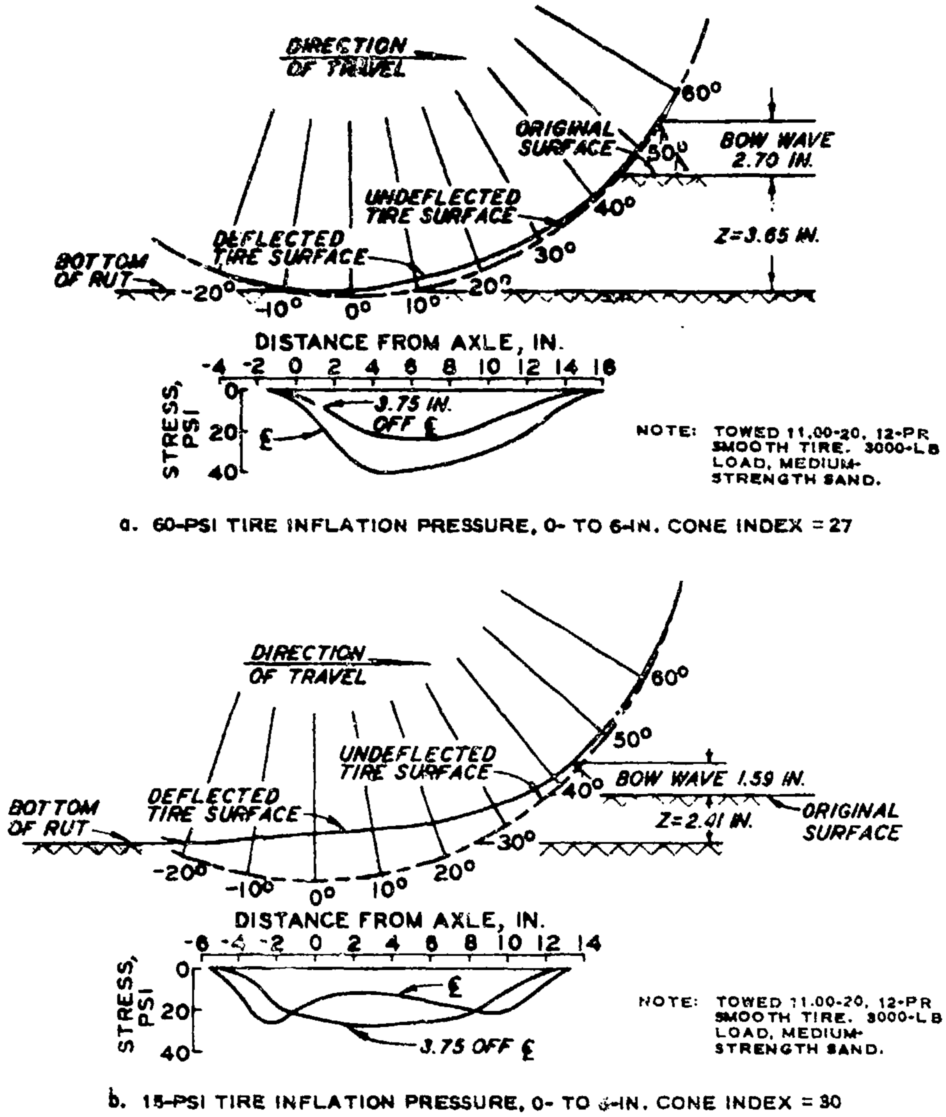

Fig. 1. Normal stresses on a tire surface
(from Technical Report M-69-2)

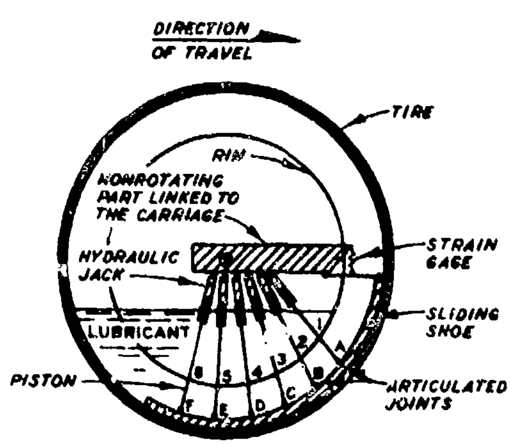

Fig. 2. Schema of the mechanical system of the experimental wheel (from Technical Report M-69-2)

reversed condition (decreasing rigidity, unfavorable rigidity distribution). This is explained by a favorable backward shift of the normal stress resultant in the first case and an unfavorable forward shift of the resultant in the second. Although conventional tires could not be outperformed, the test results strongly supported the initial working hypothesis that tire performance on sand can be improved by controlling local tire rigidity.

5. The concept of the experimental wheel was based on the characteristic variation with inflation pressure (tire rigidity) of the interface stress for tires on sand. Similar phenomena have not been observed for tires on clay. Characteristically the distribution of normal stresses beneath tires on clay is very nearly uniform over the contact area, and these "stresses remain uniformly distributed for a wide range of deflections"* (i.e. inflation pressure or rigidity patterns). This fact is illustrated in fig. 3.

6. There was no reason, therefore, to expect any performance variation on clay by changing the tire rigidity pattern. Nevertheless, since the experimental wheel was at hand, a test series was run on clay of different strengths to follow the usual WES procedures of testing running gears on both sand and clay. In addition, even negative results of the clay tests--as the case turned out--would be further proof of the interdependence of stress and rigidity patterns on sand.

Purpose and Scope

7. The purpose of this study was to determine experimentally whether the tire rigidity distribution at the soil-tire interface influences the performance of tires on clay in a way similar to that observed for tires on sand, or in any other way.

8. Testing was restricted to one clay, locally designated buckshot clay and classified CH according to the Unified Soil Classification System.

* D. R. Freitag, A. J. Green, and N. R. Murphy, "Normal Stresses at the Tire-Soil Interface in Yielding Soils," Soil Stresses, Foundation Settlement, and Caisson Stability, Record No. 74, pp 1-18, 1965, Highway Research Board, Washington, D. C.

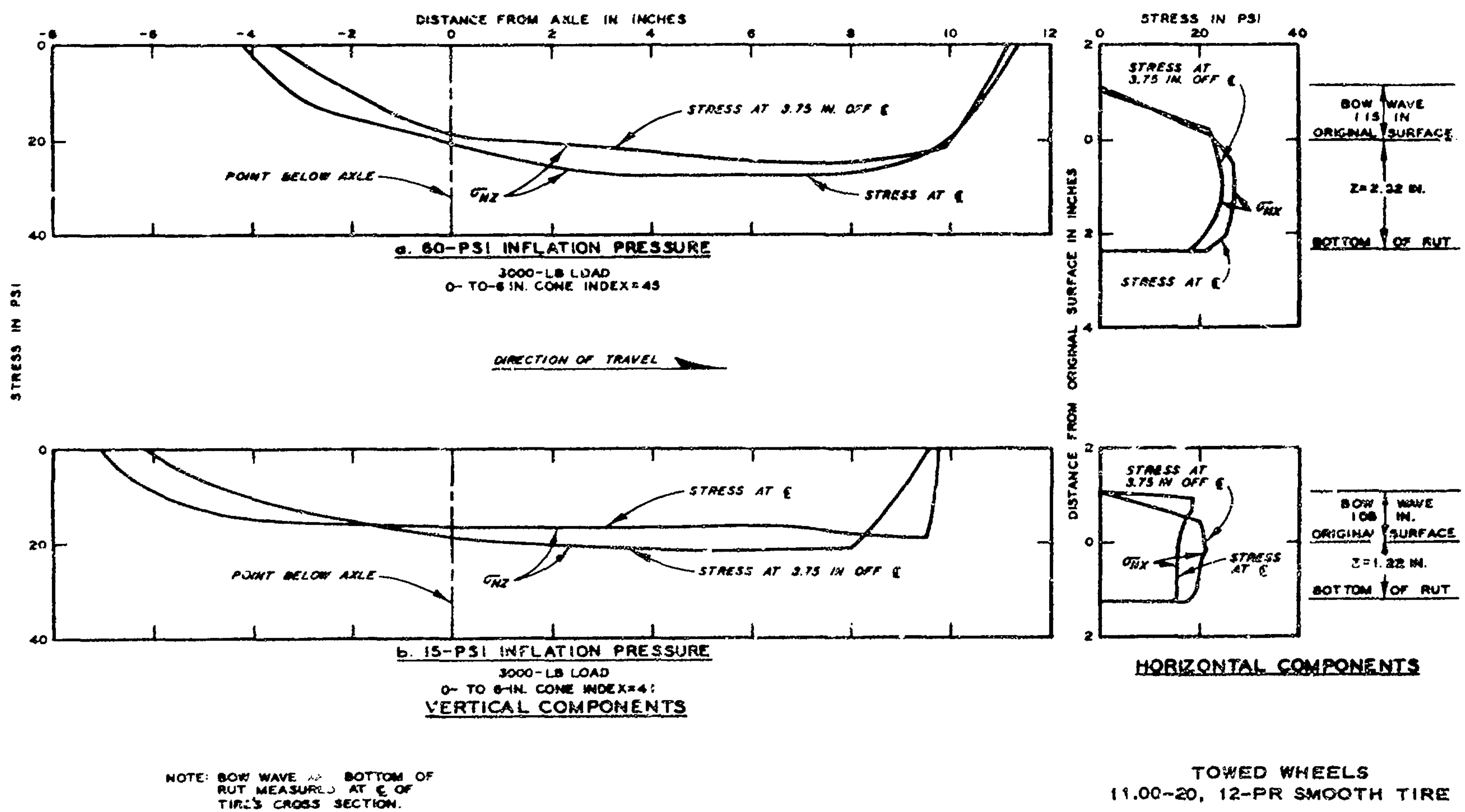

Fig. 3. Normal stresses at tire surface in clay (from Highway Research Board Record No. 74)

The test plan called for two soil strength levels, 0- to 15-cm* cone penetration resistance C of 140 and 210 kN/m^2; but because of the difficulties in preparing homogeneous clays at preestablished strength levels, other soil strengths also were tested. The procedures for soil processing and the test technique are described in Technical Report No. 3-666.** The experimental wheel was tested under two axle loads, 4000 and 4500 N, with favorable, unfavorable, and neutral rigidity† distributions. The programmed-increasing-slip test technique was used throughout the series. Approximately 30 tests were run, including some comparison tests with the internal system inoperational (base-line tests). However, just as for the sand test series, not all tests could be included in the analysis.

Data Analysis

9. Several problems arose in data reduction and subsequent data analysis that were not encountered during the sand testing program. The main problem was: What condition should be used as a reference for comparing tire performance for various rigidity patterns? This problem will be discussed briefly.

10. Tire performances on sand show a clearly identifiable maximum in their pull-slip relation, while tires on clay do not (fig. 4). Therefore, the maximum pull point was quite naturally used for a performance comparison for sand. For clay, an alternative had to be found, and it became customary to compare tire performance on clay at the 20% slip condition, which usually lies at the beginning of the range where the pull tends to stabilize (fig. 4b).

11. However, the definition of slip--and thus the fixation of a

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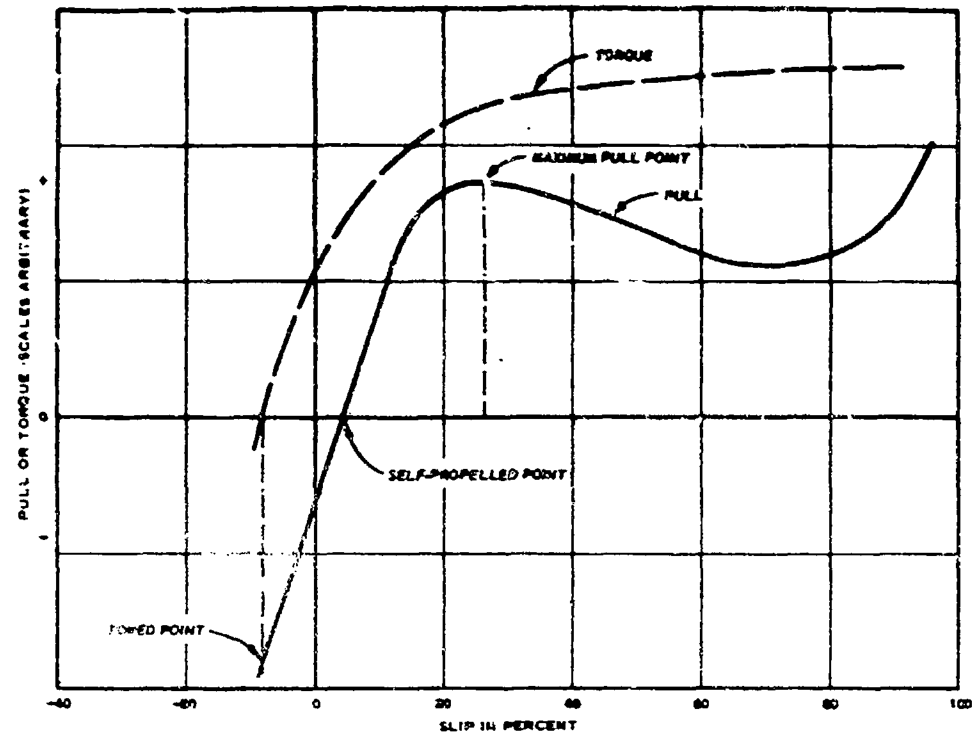
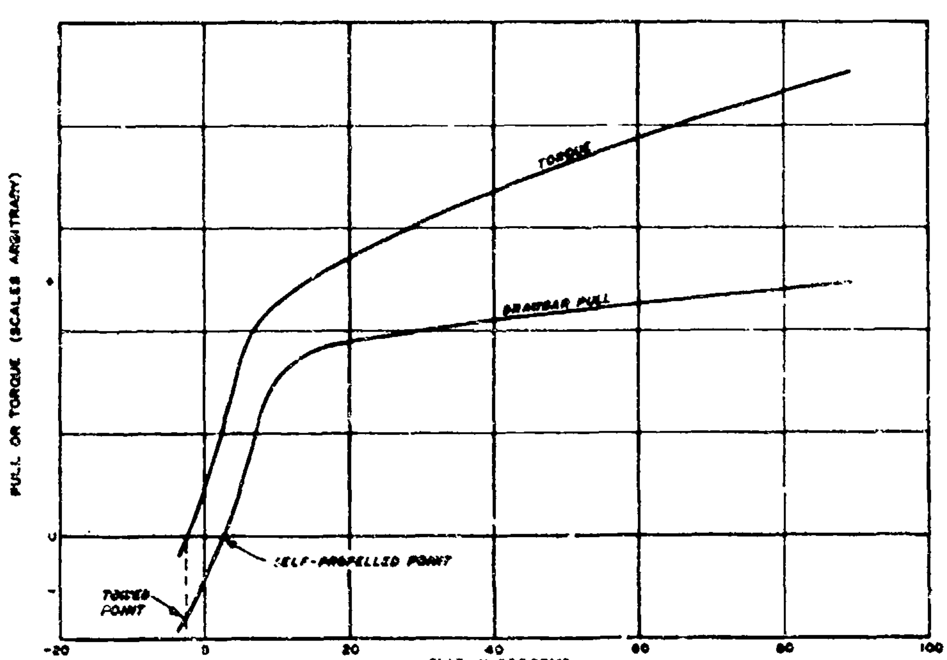
* A table of factors for converting metric to British and British to metric units of measurement is presented on page vii.

** J. L. McRae, C. J. Powell, and R. D. Wismer, "Performance of Soils Under Tire Loads; Test Facilities and Techniques," Technical Report No. 3-666, Report 1, Jan 1965, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

† No rigidity variation over the interface; results from loading all internal jacks equally.



a. YUMA SAND



b. CLAY

Fig. 4. Sample pull-slip and torque-slip curves (from Technical Report No. 3-666)

reference point--is contingent upon the rolling radius of the tire. The true in-soil rolling radius can be determined only with great difficulty; and for ordinary tire tests, the hard-surface deflection radius is customarily taken as a substitute. In fact, the error involved is small in all cases for conventional tires.

12. For the experimental wheel, however, this approximation procedure could not be applied because the internal system of hydraulic jacks not only influenced the rigidity pattern but also the tire geometry. The favorable rigidity distribution with high pressures beneath the wheel axle is likely to produce a maximum rolling radius,* and the unfavorable rigidity distribution a minimum rolling radius. Thus, the two extreme rigidity distributions are associated with extreme rolling radii, which results in extreme positive and negative errors in determining slip. Only if these errors can be shown to be negligibly small can a given slip value serve as a basis for performance comparison.

13. This, however, is not the case for the conditions under which the experimental wheel was tested. As in the earlier tests on sand, the test series on clay was programmed for a nominal forward speed of 0.76 m/sec for the zero-slip condition. With a nominal tire radius of 0.336 m, this yields a rotational speed of the tire of $\omega = 2.26$ radians/sec (0.36 rps), which is held constant during a test run. With the expression for slip being $s = 1 - (v/R\omega)$, a nominal speed $v = 0.607$ m/sec is obtained for 20% slip. If a $\pm 5\%$ error in the determination of the in-soil rolling radius R is allowed, the slip values obtained are

$$s_1 = 1 - \frac{0.607}{1.05 \times 0.336 \times 2.26} = 0.239 \ (24\%)$$

$$s_2 = 1 - \frac{0.607}{0.95 \times 0.336 \times 2.26} = 0.159 \ (16\%)$$

compared to the nominal slip value of 20%.

14. Thus, a 5% error in the radius (which is a conservative

* Defined here as the vertical distance between wheel axle and periphery.

assumption in view of the complexity of the system) generates a 20% error in the slip computation. This precludes a fixed slip value serving as a basis for performance comparison, since the geometric test data (among them the rolling radius) of the experimental wheel are the least reliable ones.*

15. In addition, P/W versus slip curves were unusually ill defined from the test data, precluding in many instances even the recognition of a trend (fig. 5b). The most likely explanation for this tremendous scatter is a mechanical instability of the entire hydraulic jack-tire-carriage

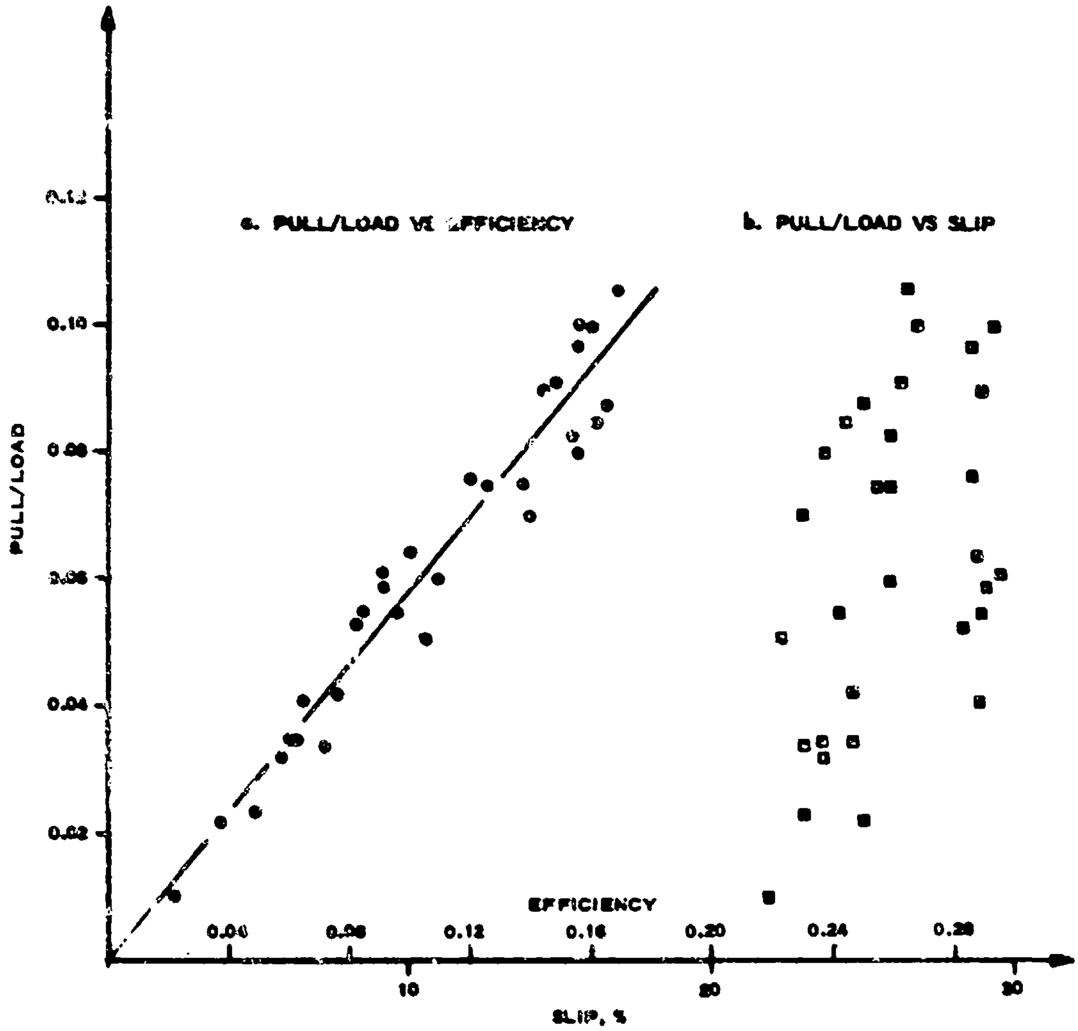


Fig. 5. Performance of experimental wheel in clay (test 69-13)

* Wiendieck, op. cit., p 1.

system, which was working in the critical domain of its maximum torque capacity of about 500 m-N for the majority of the tests.

16. The plateau of the pull-slip curve (fig. 4b) was not reached in the tests on low-strength soil test sections, even at large values of slip, and the P/W ratio barely went beyond the extremely low value of 0.1 (fig. 5b). For the few tests on high-strength soil, the plateau was reached at very low values of slip (figs. 8d, 9c, and 9d), and the scatter in the pull-slip relations was somewhat reduced so that a pull-slip relation could be defined.

17. In view of the both theoretical and practical impossibility of using pull-slip curves as a basis for comparison, another way of interpreting the test data had to be found. After considerable searching, only the P/W versus efficiency (E) relation was found to present a definite, recognizable trend for all tests as exemplified in fig. 5a, which represents the same test as fig. 5b. Plotted in this manner, the data points show a linear relation between P/W ratio and E . A decision was therefore made to compare the behavior of the wheel with various rigidity patterns on the basis of the $\frac{P/W}{E}$ ratio, which, by virtue of the linearity of the relation, is a constant and represents the tangent of the slope of the line of best fit (fig. 5a).

18. This meant a radical departure from the way the previous sand study was analyzed, and precludes a direct comparison of the performance of the experimental wheel in sand and clay. In fact, both P/W ratio and E are, in themselves, performance parameters. A change in their ratio (slope of the straight line) indicates an increase of one of them at the expense of the other, while for the earlier sand tests, both the P/W ratio and E were dealt with independently. Thus, for the sand tests, truly different performance levels could be associated with each rigidity pattern in that P/W ratio and E concurrently were either higher or lower than a given reference value. The method of comparison adopted for this study of the experimental wheel on clay permits only the detection of variations of tire behavior rather than of performance, the behavior being characterized by the slope of the P/W versus E curve. This considerably reduces the

significance of the study, but the test data did not permit proceeding otherwise.

19. It must be pointed out that a straight-line P/W versus E relation is theoretically possible only for a limited lower slip range. To illustrate this, convenient numerical values were associated with the sample curves of fig. 4. If the vertical scale of fig. 4b represents 1000 N and 1000 m-N per unit for pull (P) and torque (M), respectively, and if $W = 10{,}000$ N and $R = 0.5$ m, the P/W ratio and E (where $E = Pr(1 - s)/M$) can be calculated from the sample curves for various slip values. The resulting P/W versus E plot is given in fig. 6. The lower portion of this curve can indeed be represented as a straight line having, in this particular case, a small intercept with the E axis (fig. 6).

20. If correctly interpreted, such P/W versus E plots reveal as much information as the commonly used pull-slip and torque-slip curves. Maximum efficiency and pull are well represented, and the breakdown of the

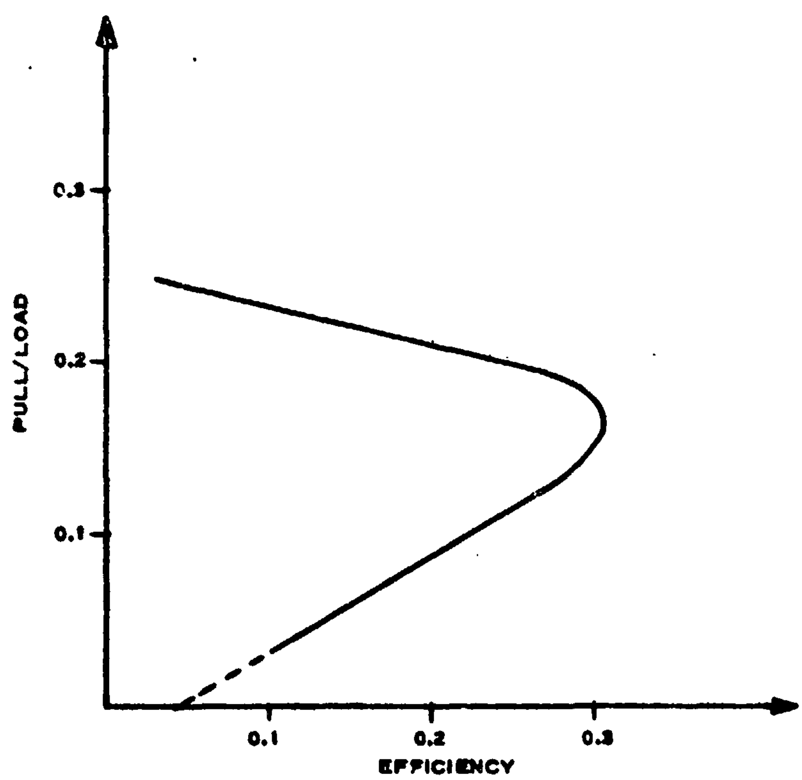


Fig. 6. Pull/load versus efficiency at various slip values. Sample curve for conventional tires

relation into distinct segments is even more clearly shown than by the usual pull-slip curve (fig. 4b). In addition, such curves are not affected by questionable definitions of the rolling radius and thus slip, since slip, although included in the current definition of efficiency, does not affect its value. In fact, efficiency is defined as

$$E = \frac{Pv}{M\omega}$$

where

v = forward speed

ω = rotational speed

P , v , M , and ω are directly measurable quantities, whereas slip is a derived quantity for a given rolling radius. With $s = 1 - (v/R\omega)$, the current expression of $E = PR(1 - s)/M$ is obtained.

21. A comparison of the sample curve (fig. 6) with an actual data plot (fig. 5a) clearly shows that final level of the pull was not reached in the test, a fact that could hardly have been established from the greatly scattered data in the pull-slip plot (fig. 5b). The available torque was not sufficient for the wheel to leave the initial domain of steeply increasing pull, although the measured high slip values of more than 20% (fig. 5), taken at face value, normally would indicate the contrary.

22. It has been pointed out earlier that at 20% slip the wheel in most cases operates near the limit of the required torque. The torque oscillates heavily around the limit value, presumably because of the fluctuating friction losses of the internal system. The pull also oscillates heavily, but efficiency and pull oscillate synchronously; this resulted in the neat lineup of the data points in fig. 5a. On the other hand, slip, essentially a speed ratio rather than a force or energy ratio, oscillates along another pattern and, therefore, is not suitable for analyzing data in this case.

23. These problems could have been reduced considerably by running the tests with lighter loads. However, as discussed in detail in Technical

Report M-69-2,* for the tested system to be effective, a large contact surface is required, and this could be obtained only by the chosen combination of heavy loads and low soil strength. Otherwise, the test results would certainly have been inconclusive.

Data reduction

24. Comparison of the tests in terms of tire performance was impossible and only a much less significant comparison of tire behavior was found to be feasible. Therefore, it was decided not to examine every test in the same meticulous manner, but rather to rely on some sample test groups, each comprising a test with favorable and unfavorable rigidity distribution and, if possible, base-line tests. Only a few of such sample groups could be identified with all tests being run under otherwise comparable conditions.

25. For these tests, the P/W versus E curves were plotted by using the raw data and an assumed rolling radius of 0.336 m on which the slip computation was based. Thus, the E values were not affected by an erroneous rolling radius, since the errors in slip and rolling radius cancel in the definition of E . On the other hand, E contains an error due to the friction of the internal system, which must be eliminated for a valid comparison. To eliminate this error, the simplified graphic solution was applied to the statics of the internal system as described in Technical Report M-69-2.* This method yielded the normal components of that fraction of the piston forces that caused friction at the sliding shoe-tire interface, as well as the friction coefficient, which turned out to be unchanged from the previous test program on sand, i.e. 0.1. These data, in conjunction with the approximately known tire geometry, provided the information necessary to compute the internal moment M_i . A corrected E was then determined:

$$E = \frac{PR}{M - M_i} (1 - s)$$

and a corrected P/W versus E curve was drawn.

26. In determining the internal frictional torque loss, no attempt

* Wiendieck, op. cit., p 1.

was made to follow its oscillations, which were manifested in the fluctuating readings of the internal strain gage (fig. 2). Instead, a mean value of the strain-gage readings was used, in the belief that the expected results of limited interest would not warrant an out-of-proportion effort for accuracy. For the same reason, the P/W versus s curves were assumed for the investigated domain to be straight lines passing through the origin. Only the high-strength soil test results (fig. 9, page 16) were treated differently.

Test results

27. The first of the selected test groups represented tests on soil of a relatively low strength ($C \approx 180$ kN/m^2; fig. 7). The test results obtained with favorable rigidity distribution (fig. 7a) and unfavorable rigidity distribution (fig. 7b) show little difference in the corrected P/W versus E line (solid line); the $\frac{P/W}{E}$ ratios are almost identical (0.46 and 0.44, respectively). The corresponding base-line test (fig. 7c; different scale) did not yield any data in these low P/W and E ranges and, therefore, did not lend itself to a comparison with the other two tests. It has been included here as proof that the complete picture of the characteristic P/W versus E curve (fig. 6) could indeed be obtained under these conditions if the internal system remained inoperational, i.e. without friction losses. Therefore, the internal friction losses were responsible for the low performance level of the two other tests.

28. The same results were obtained for a stronger soil condition of $C = 220$ kN/m^2 (fig. 8), the only difference being the ability of the wheel to reach a slightly higher performance level both in terms of P/W ratio and E ; but the behavior of the wheel in terms of the $\frac{P/W}{E}$ ratio again shows the same value of about 0.45 for the favorable (fig. 8a) and the unfavorable (fig. 8b) rigidity distributions. The corresponding base-line test (figs. 8c and 8d) resulted in relations with the characteristic features of normal P/W versus E and P/W versus s curves.

29. On a rather strong soil ($C = 360$ kN/m^2; fig. 9b), the wheel behavior was different from that on the softer soils, but no difference in the results was obtained for favorable (fig. 9a) and unfavorable (fig. 9b) rigidity distributions. In both cases, the torque capability of the

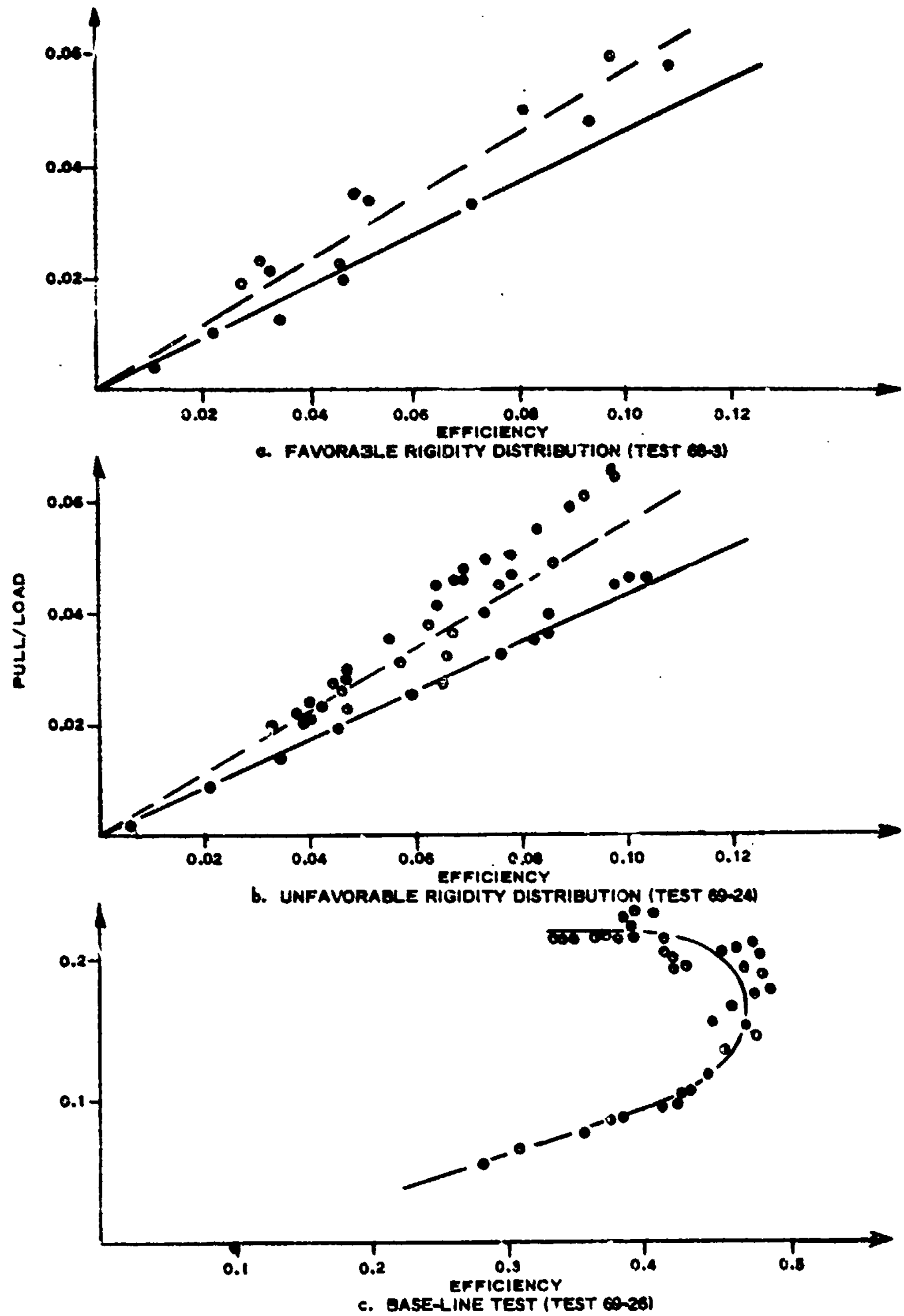


Fig. 7. Relation of pull/load to efficiency, experimental wheel in clay, C ≈ 180 kN/m^2; load = 4000 N

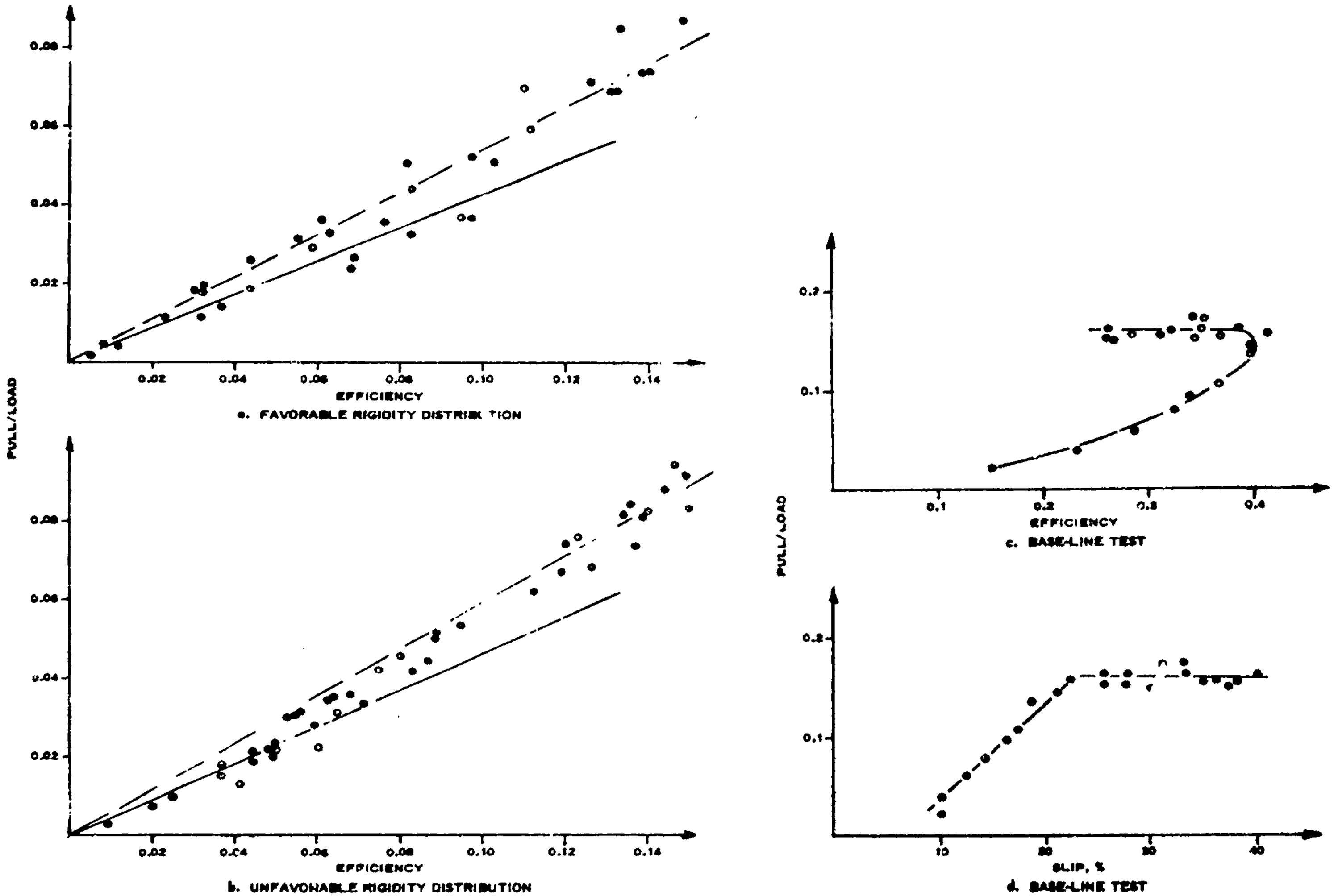


Fig. 8. Relation of pull/load to efficiency and slip, experimental wheel in clay (test 69-3), C = 220 kN/m^2; load = 4500 N

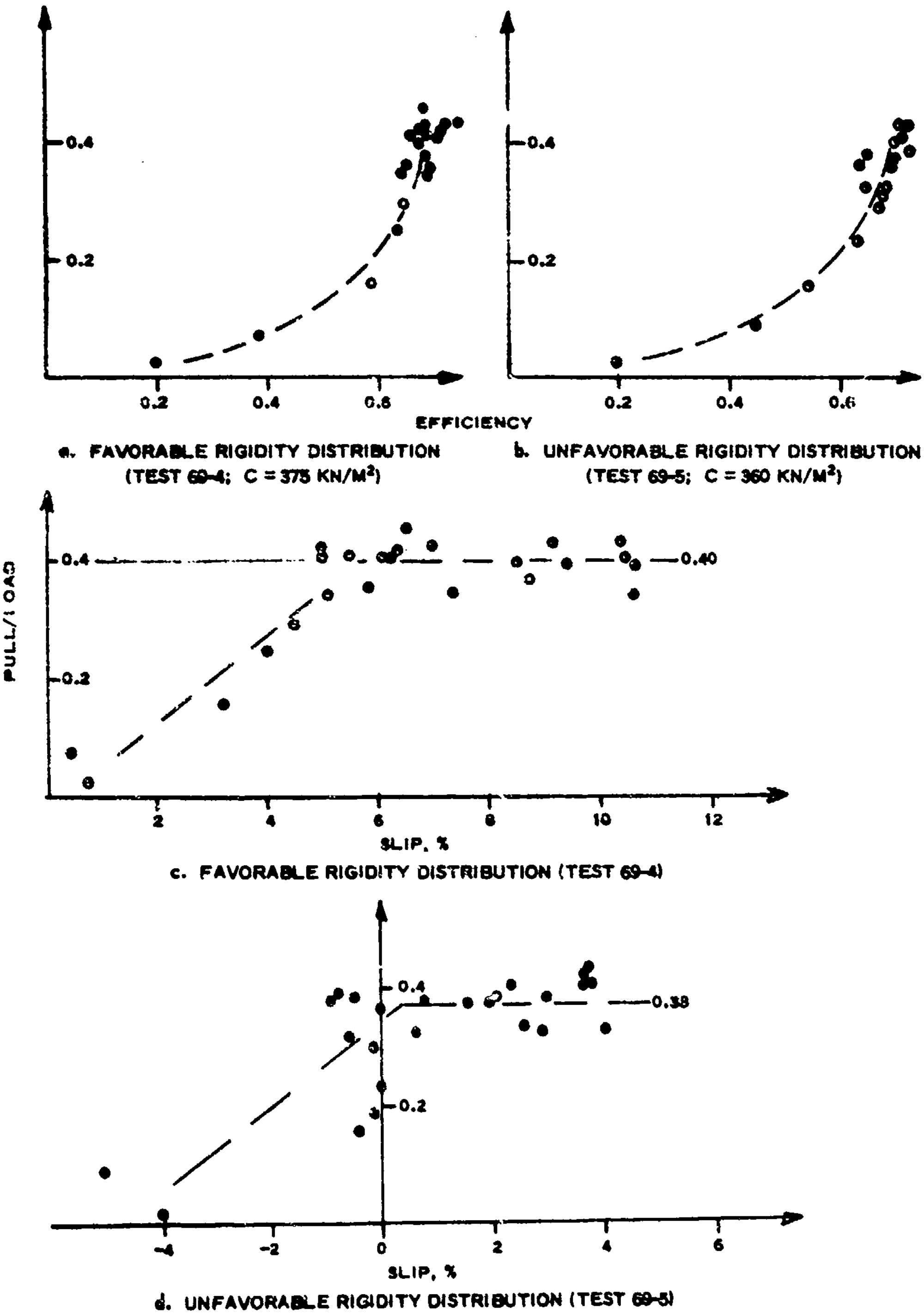


Fig. 9. Relation of pull/load to efficiency and slip, experimental wheel in clay; load = 4500 N

carriage was sufficient to make the wheel cover the full performance range, including the pull plateau. This allowed the usual pull-slip relations to be drawn (figs. 9c and 9d); therefore, the cumbersome procedure required to draw the corrected P/W versus E curve was omitted in this case, and the comparison was based on the pull-slip curves.

30. Except for a slight shift in the slip range, the pull-slip curves for the favorable and unfavorable rigidity distributions (figs. 9c and 9d) are almost identical. The slight difference between the P/W ratios at the plateau (0.40 and 0.38, respectively) is well within the scatter limits of normal tire tests. The shift of the slip range in figs. 9c and 9d was primarily a result of the difference between the actual rolling radii. The greater radius generated by the favorable rigidity distribution resulted in a higher slip (and vice versa) than the normal slip based on the assumed radius of 0.336 m (see example in paragraph 13).

Conclusions and Recommendation

Conclusions

31. It is concluded that:

a. The rigidity pattern at the soil-tire interface has no effect on tire behavior on clay because the pressure distribution beneath tires on clay does not vary qualitatively with tire rigidity distribution, as evidenced by the unvariability of the pressure distribution with inflation pressure or deflection (fig. 3).

b. The principle of controlled circumferential rigidity appears to be valid for those soils in which there is a qualitative change in interface pressure distribution as a function of inflation pressure or deflection.

Recommendation

32. It is recommended that no further tests be made with the experimental wheel, since the basic problems associated with it have been solved.